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CURIUM DATA SHEETS

(Title Unclassified)

S. J. Rimshaw
E. E. Ketchen

OAK RIDGE NATIONAL LABORATORY
operated by
UNION CARBIDE CORPORATION
for the
U.S. ATOMIC ENERGY COMMISSION

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ORNL-4044

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ISOTOPES DEVELOPMENT CENTER

CURIUM DATA SHEETS

S. J. Rimshaw
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ISOTOPES DIVISION

NOVEMBER 1966

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CURIUM DATA SHEETS

I. CURIUM-244 — REFERENCE COLUMN

A. CURIUM-244 METAL — HALF-LIFE: 18.1 y — 1

1. Composition

a. Radionuclidic abundance — 3

Element	Minimum, %	Maximum, %
Cm	99.5	99.8
Am	0.5	0.2

An average ^{244}Cm product will have the following analysis:

Isotope	% Abundance
^{244}Cm	95.5
^{245}Cm	1.6
^{246}Cm	2.7
^{243}Am	0.2

b. Radiochemical purity

Because of their long half-lives, the ^{245}Cm ($T_{1/2}$ = 8000 y), ^{246}Cm ($T_{1/2}$ = 6600 y), and ^{243}Am ($T_{1/2}$ = 8000 y) impurities act as inert diluents and contribute <0.1% of the total source power.

The radiations from these impurities are weak gammas or alpha particles and can be neglected because they are readily shielded. The prompt gammas and neutrons from the spontaneous fission will be only a few percent of that obtained from spontaneous fission of ^{244}Cm.

Since the ^{244}Cm decays to ^{240}Pu, the plutonium content in the sample will slowly build up after the final purification step as shown in the following table.

Time, months	^{240}Pu, %
0	0
7.2	2.7
18	6.4
36	12.3
90	27.8

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REFERENCE COLUMN

2. Specific Power

a. 2.67 watts/g of metal (95.5% ^{244}Cm content) — 2, 3, 4

It is assumed that there are 81 curies/g of ^{244}Cm and that there are 34.3 watts/kilocurie of ^{244}Cm.

b. 77.4 curies of ^{244}Cm per gram of metal — 2, 3, 4

3. Radiation

a. Alpha particles — 2, 5

Nuclide	Max E, Mev	Avg E, Mev	Abundance, %	w/kilocurie	Particles w^{-1} sec^{-1}
^{244}Cm	5.801	5.801	76.7	34.3	0.825×10^{12}
	5.759	5.759	23.3	____	0.252×10^{12}
Total alpha power				34.3	

The volume of helium from alpha decay as a function of decay time is given in the following table.

Volume of Helium as a Function of Decay Time

cm^3 of He per g of ^{244}Cm (standard conditions)	Time	
	Years	Half-lives
6.15	1.8	0.1
11.8	3.6	0.2
17.3	5.4	0.3
22.1	7.2	0.4
26.9	9.1	0.5
31.2	10.9	0.6
35.3	12.7	0.7
39.1	14.5	0.8
42.6	16.3	0.9
45.9	18.1	1.0
59.3	27.1	1.5
68.9	36.2	2.0
80.3	54.3	3.0
86.1	72.4	4.0
88.9	90.5	5.0
91.7	181.0	10.0

REFERENCE COLUMN

b. Beta particles — none

c. Gamma

The gammas come from three sources. First there are the gammas associated with the alpha decay of ^{244}Cm. Secondly, there are the prompt gammas from spontaneous fission. The fission-product gammas constitute the third gamma source. The gamma-emission rates are given in the following table. 2, 3, 5

Gamma-emission rate, photons sec^{-1} w^{-1} of ^{244}Cm	Photon energy, Mev
^{244}Cm gammas	
0.252×10^{12}	0.042
5.80×10^{7}	0.10
1.40×10^{7}	0.15
Prompt gammas from spontaneous fission	
4.34×10^{6}	1.0
1.084×10^{6}	1.5
1.15×10^{6}	2.3
2.03×10^{5}	3.0
2.71×10^{5}	5.0
Fission-product gammas	
3.84×10^{6}	0.63
1.42×10^{6}	1.1
1.66×10^{6}	1.55
3.20×10^{5}	2.38
4.73×10^{5}	2.75

d. Bremsstrahlung — none

e. Neutrons

4.19×10^{6} neutrons sec^{-1} w^{-1} of ^{244}Cm from spontaneous fission 5, 6, 7
(Half-life for spontaneous fission is 1.4×10^{7} y)

1.51×10^{5} neutrons sec^{-1} w^{-1} of ^{244}Cm from (α,n) reaction on oxygen in Cm_2O_3 5

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REFERENCE COLUMN

The energy distribution of spontaneous fission neutrons from ^{244}Cm is given in the following table. 3

Spontaneous Fission Neutrons From Curium-244

Energy, Mev	Abundance, neutrons sec^{-1} w^{-1} of ^{244}Cm
0.3-0.4	1.51×10^5
0.4-0.6	3.13×10^5
0.6-0.8	3.20×10^5
0.8-1.0	2.77×10^5
1.0-1.2	2.84×10^5
1.2-1.4	2.80×10^5
1.4-1.6	2.44×10^5
1.6-1.8	2.19×10^5
1.8-2.0	1.98×10^5
2.0-2.2	1.80×10^5
2.2-2.4	1.65×10^5
2.4-2.6	1.58×10^5
2.6-2.8	1.30×10^5
2.8-3.0	1.08×10^5
3.0-3.2	1.01×10^5
3.2-3.4	0.97×10^5
3.4-3.6	0.93×10^5
3.6-3.8	0.75×10^5
3.8-4.0	0.79×10^5
4.0-4.4	1.04×10^5
4.4-4.8	0.86×10^5
4.8-5.2	0.65×10^5
5.2-5.6	0.50×10^5
5.6-6.0	0.40×10^5
6.0-6.4	2.95×10^4
6.4-6.8	2.12×10^4
6.8-7.2	1.47×10^4
7.2-7.6	1.12×10^4
7.6-8.0	0.90×10^4
8.0-8.8	1.01×10^4
8.8-9.6	2.95×10^3
9.6-10.4	3.1×10^3
10.4-11.2	2.05×10^3
11.2-12.8	1.40×10^3

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REFERENCE COLUMN

The energy distribution of neutrons occurring as a result of the collision of fast alpha particles from ^{244}Cm decay with oxygen atoms in Cm_2O_3 is given in the following table. 3

Neutrons From (α,n) Reactions With Oxygen

Energy, Mev	Abundance, neutrons sec^{-1} w^{-1} of ^{244}Cm
0.2	1.62×10^2
0.4	0.68×10^3
0.6	0.83×10^3
0.8	1.69×10^3
1.0	2.70×10^3
1.2	0.43×10^4
1.4	0.61×10^4
1.6	0.83×10^4
1.8	1.01×10^4
2.0	1.19×10^4
2.2	1.33×10^4
2.4	1.40×10^4
2.6	1.40×10^4
2.8	1.37×10^4
3.0	1.22×10^4
3.2	1.01×10^4
3.4	0.79×10^4
3.6	0.50×10^4
3.8	3.02×10^3
4.0	2.01×10^3
4.2	1.37×10^3
4.4	0.86×10^3
4.6	0.72×10^2

4. Critical Mass

The critical mass of unreflected and reflected spheres of ^{244}Cm and $^{244}Cm_2O_3$ have been calculated by C. W. Craven, Jr., at ORNL using the cross-section data available as of November 1965. The results, shown in the following table, agree within 10% of the results obtained in the replacement experiment at Los Alamos. 8

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REFERENCE COLUMN

Calculated Critical Mass of ^{244}Cm and $^{244}Cm_2O_3$

Core		Reflector			Critical
Mixture	Density, g/cm^3	Mixture	Thickness, cm	Critical mass, kg	radius, cm
Cm[a]	14.0	Bare	--	12.5	5.97
Cm_2O_3[a]	10.60	Bare	--	21.1	7.8031
Cm_2O_3	9.01	Bare	--	29.2	9.1803
Cm_2O_3	10.60	Au-H_2O	4.0-15.0	11.9	6.4540
Cm_2O_3	10.60	Au-H_2O	2.0-7.5	13.5	6.7188
Cm_2O_3	10.60	Au-H_2O	0.5-2.0	16.5	7.1966

Critical Mass Equations

Cm: $M_c = 2450/\rho^2$ (kg) Cm_2O_3: $M_c = 2370/\rho^2$ (kg)

[a]Assumed composition: 98.07 wt % ^{244}Cm and 1.93 wt % ^{241}Pu.

5. Compatibility With Materials of Containment

6. Thermophysical Properties

a. Density

13.51 g/cm^3 of metal — 9

b. Coefficient of thermal expansion

$\alpha_a = 7.5 \times 10^{-6}/°C$ — 10 (Am)

$\alpha_c = 6.2 \times 10^{-6}/°C$

c. Specific heat and enthalpy

(1) Specific heat

0.0270 cal g^{-1} $°C^{-1}$ — 11 (Nd)

(2) Enthalpy in calories

$H_t - H_o = 6.48 + 3.53 \times 10^{-3} t^2 + 1.49 \times 10^{-6} t^3$ — 12 (Nd)

(Nd temperature is 0-400°C and t is in °C)

d. Temperatures of phase transformations

(1) Melting point — 1340°C — 9

(2) Boiling point — 3100°C — 13

(Average of terbium and gadolinium boiling points)

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REFERENCE COLUMN

e. Latent heats of phase transformations

ΔH fusion 37.5 kcal/mole (Richard's rule) — 11

ΔH vaporization 77.0 kcal/mole (Trouton's rule) — 11

f. Vapor pressure

$\log_{10} P = 8.4 - 18{,}400/T$ — 14

(T is in °K and P is in torr)

This is an average of neodymium, gadolinium, and terbium.

g. Thermal conductivity

0.021 cal cm^{-1} sec^{-1} $°C^{-1}$ at 26°C — 15 (Gd)

h. Thermal diffusivity

0.575 cm^2/sec at 26°C

This value was calculated by dividing the product of the specific heat and density into the thermal conductivity.

i. Viscosity

2.5 centipoises at 1340°C — 16

j. Surface tension

500 dyn/cm — 17

k. Total hemispherical emittance

0.37 at 89°C — 18 (Pu)

l. Spectral emissivity

0.55 — 19 (Er)

A higher value of 0.9 can be assumed if the metal surface is oxidized or if impurities are present.

m. Crystallography

double hexagonal close packed — 9

a = 3.496 ± 0.003 A

c = 11.331 ± 0.005 A

n. Solubilities

Reacts strongly with water — 20

o. Diffusion rates

REFERENCE COLUMN

7. Mechanical Properties

a. Hardness

Vicker's – 97.7 — 13 (Dy)

b. Crush strength

7741 kg/cm^2 — 13 (Tm)

8. Chemical Properties

a. Heat and free energy of formation, entropy

(1) Heat of formation

Zero – by definition of standard state

(2) Free energy of formation

Zero – by definition of standard state

(3) Entropy (temperature)

$S^{\circ}_{298} = 15$ cal $°C^{-1}$ $mole^{-1}$ — 22 (Am)

b. Chemical reactions and reaction rates (oxygen, nitrogen, water, steam, hydrogen, liquid metals, other)

(1) Oxygen at room temperature – slow — 9

(2) Oxygen at elevated temperature – fast — 9

(3) Nitrogen at room temperature – very slow — 23

(4) Nitrogen at elevated temperature – slow — 23

(5) Water at room temperature – fast — 20

(6) Hydrogen at room temperature – slow — 20

(7) Hydrogen at elevated temperature – fast — 20

9. Biological Tolerances

Maximum permissible body burdens and maximum permissible concentrations of ^{244}Cm in air and water are shown in the table on the following page. — 24

10. Shielding Data

Gamma dose rates with water, iron, lead, and uranium shielding are given in Figs. 1-5 for ^{244}Cm power sources of 100, 200, 500, 1000, 2000, 5000, 10,000, and 20,000 watts. Neutron dose rates with water shielding are given in Fig. 6. Neutron dose rates on shielding with Be, CH, CH_2, or LiH can be estimated by using Fig. 6 in conjunction with Fig. 7.

Maximum Permissible Body Burdens and Maximum Permissible Concentrations for Radionuclides in Air and in Water for Occupational Exposure[24]

Radionuclide and type of decay		Organ of reference (critical organ underscored)	Max. permissible burden in total body, q(μc)	Maximum permissible concentrations, μc/cm^3 For 40-hr week Water	For 40-hr week Air	For 168-hr week Water	For 168-hr week Air
$_{96}Cm^{244}$ (α, γ)	(Sol)	Bone	0.1	2×10^{-4}	9×10^{-12}	7×10^{-5}	3×10^{-12}
		Liver	0.2	3×10^{-4}	10^{-11}	9×10^{-5}	4×10^{-12}
		Kidney	0.2	4×10^{-4}	2×10^{-11}	10^{-4}	6×10^{-12}
		Total Body	0.3	6×10^{-4}	3×10^{-11}	2×10^{-4}	9×10^{-12}
		GI (LLI)*		8×10^{-4}	2×10^{-7}	3×10^{-4}	6×10^{-8}
	(Insol)	Lung			10^{-10}		3×10^{-11}
		GI (LLI)*		8×10^{-4}	10^{-7}	3×10^{-4}	5×10^{-8}

*The abbreviations GI and LLI refer to the gastrointestinal tract and lower large intestine, respectively.

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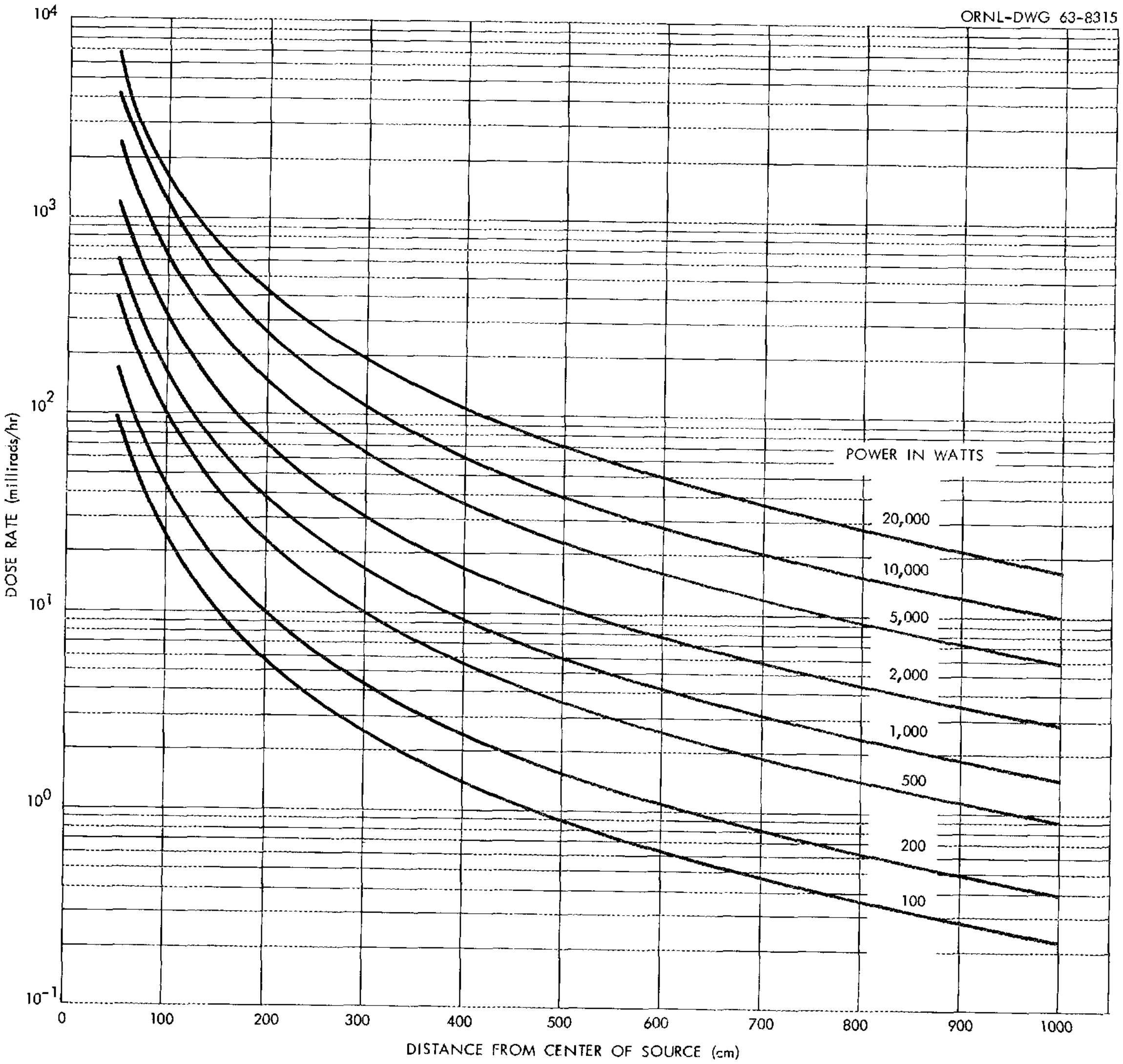

Fig. 1. Gamma Dose Rates From Unshielded Isotopic Power Sources of Curium-244 as a Function of Distance From Center of Source.

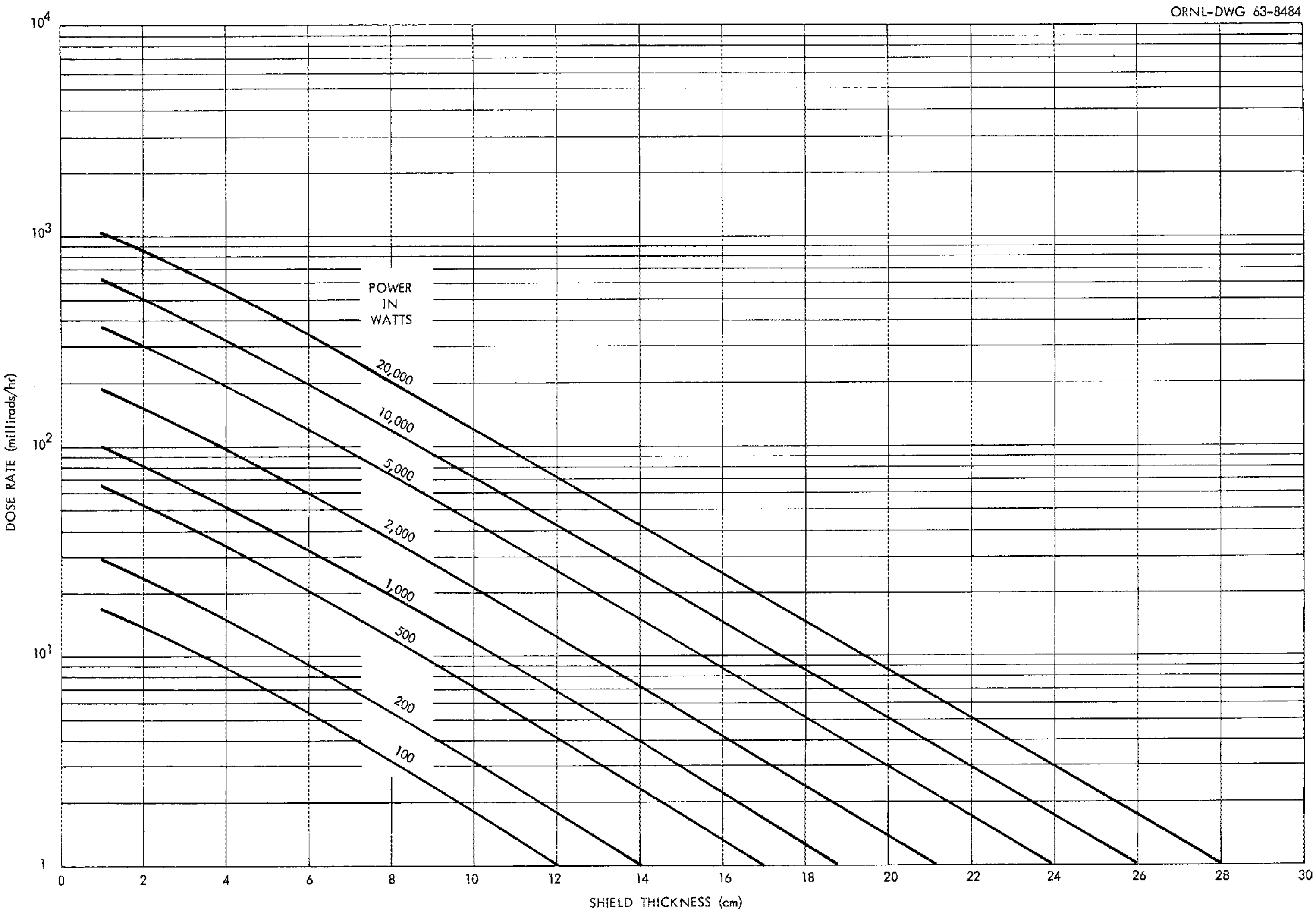

Fig. 2. Gamma Dose Rates From Iron-Shielded Isotopic Power Sources of Curium-244. Center of source to dose point separation distance = 100 cm.

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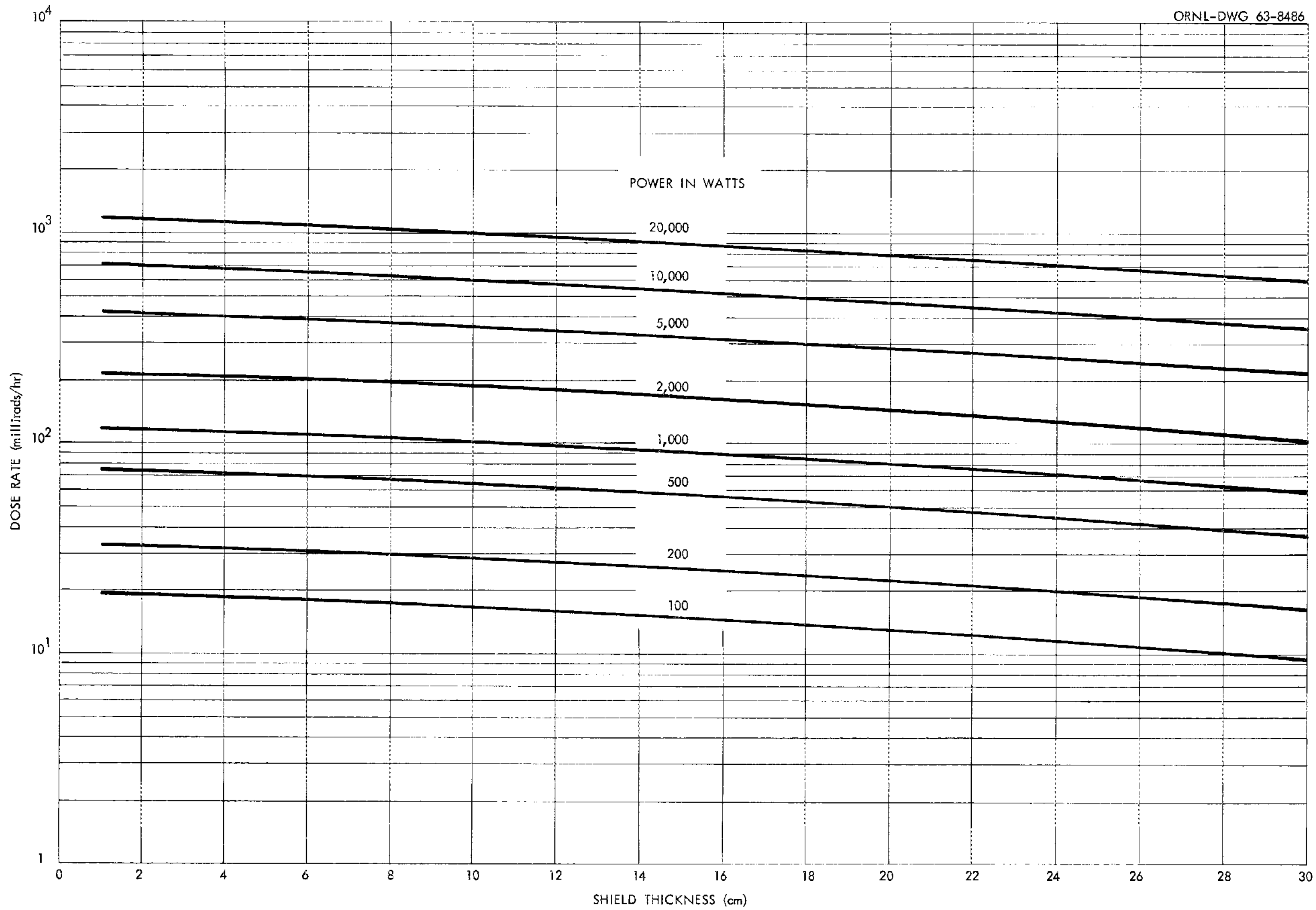

Fig. 3. Gamma Dose Rates From Water-Shielded Isotopic Power Sources of Curium-244. Center of source to dose point separation distance = 100 cm.

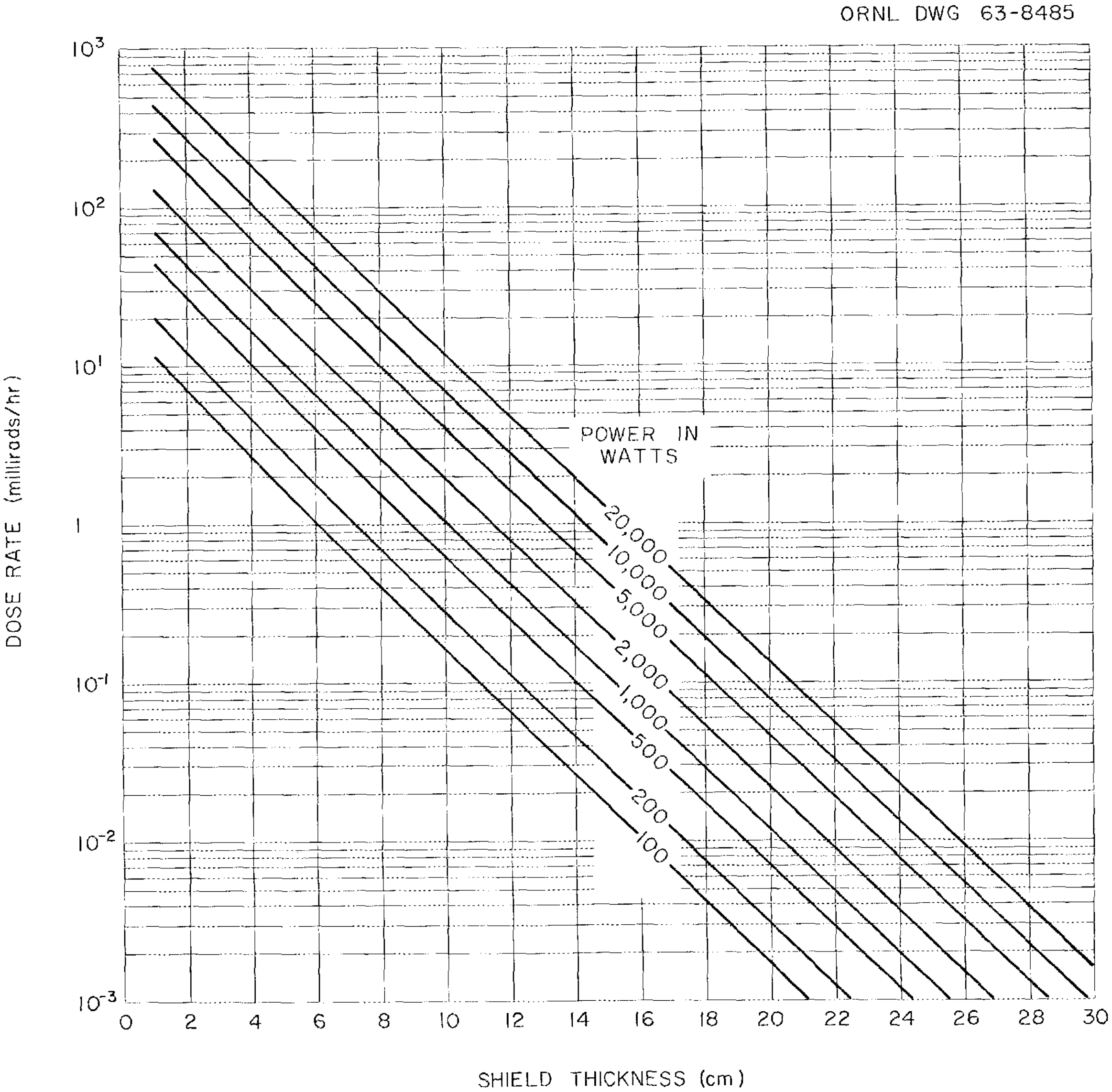

Fig. 4. Gamma Dose Rates From Lead-Shielded Isotopic Power Source of Curium-244. Center of source to dose point separation distance = 100 cm.

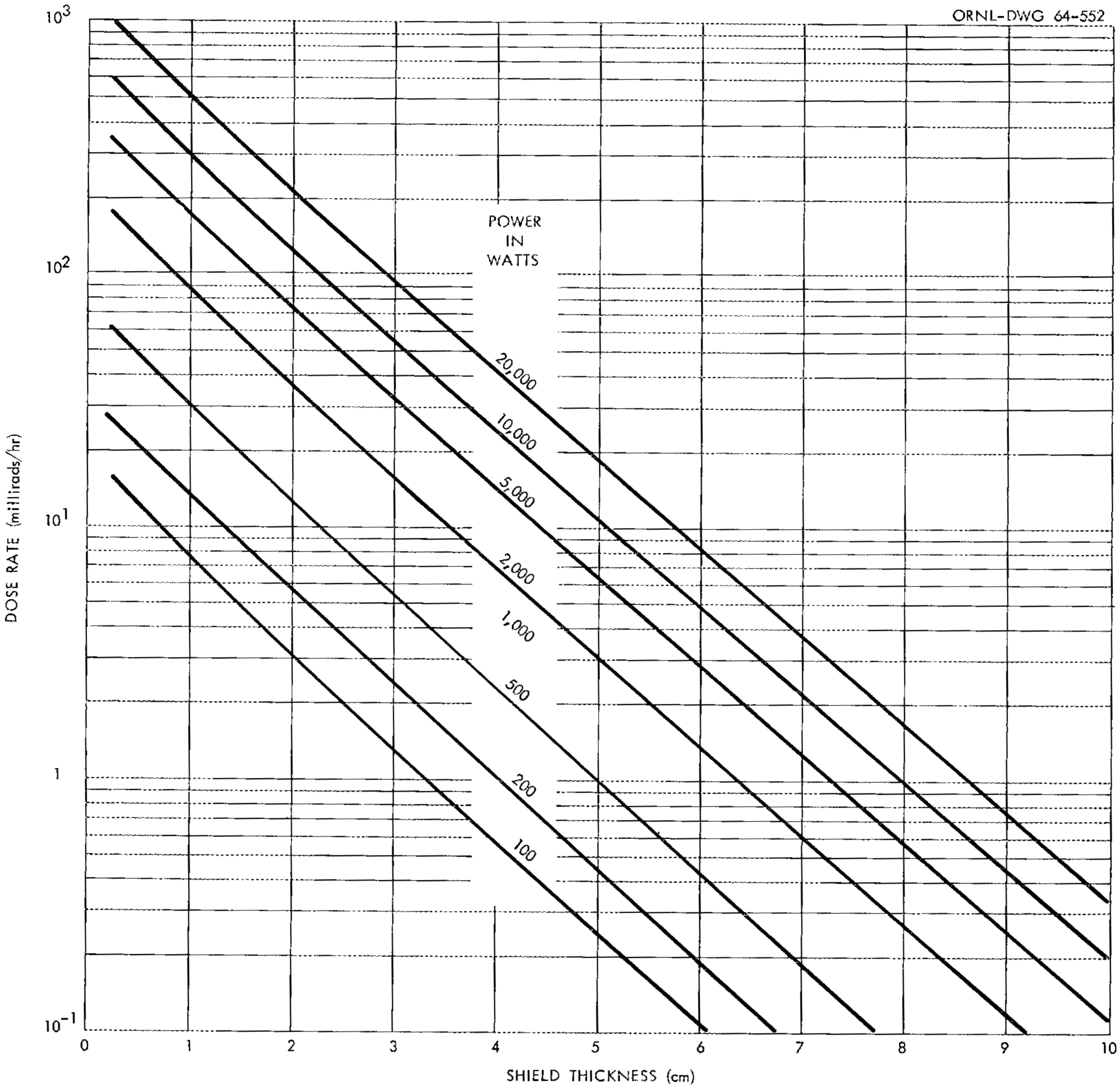

Fig. 5. Gamma Dose Rates From Uranium-Shielded Isotopic Power Sources of Curium-244. Center of source to dose point separation distance = 100 cm.

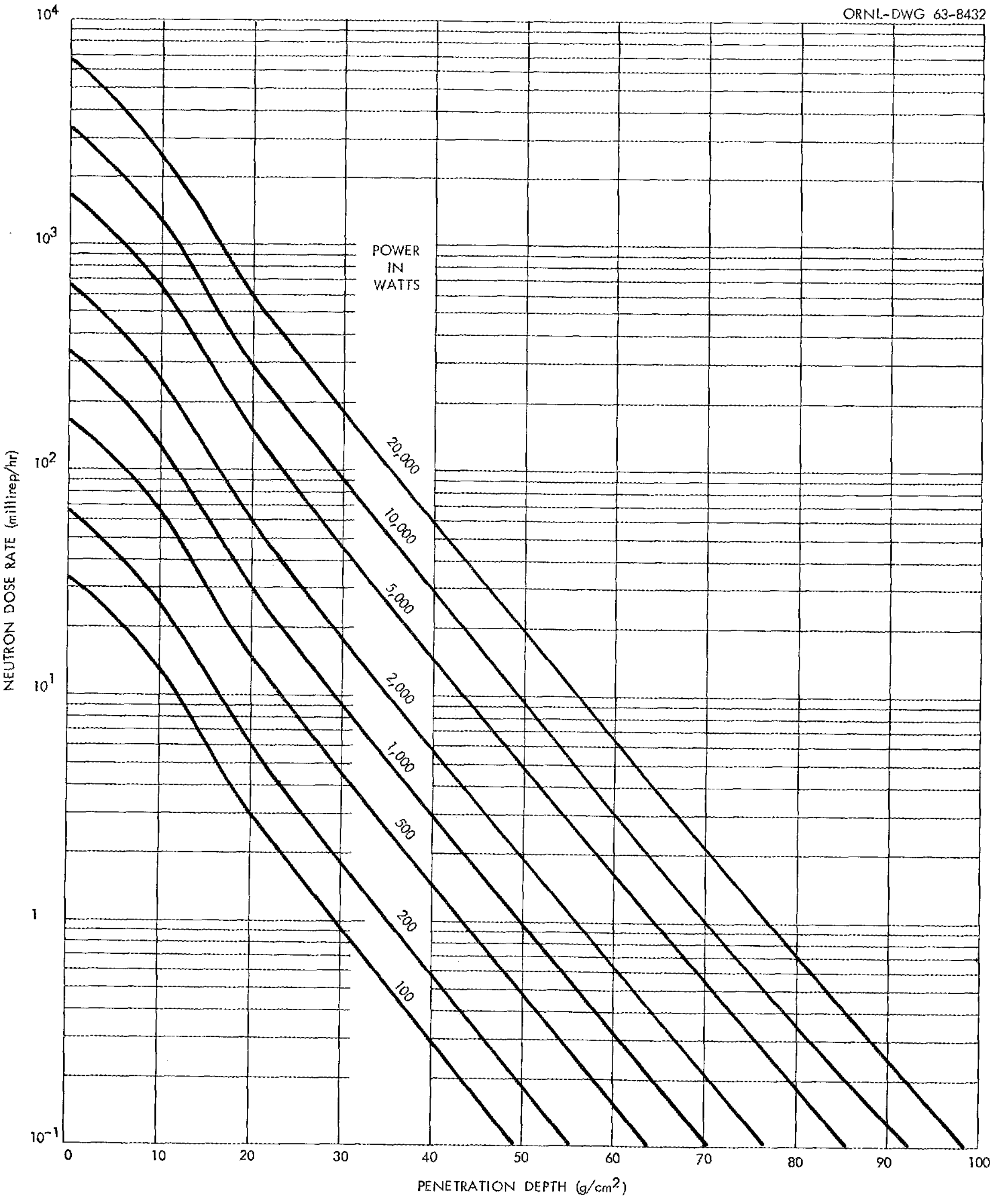

Fig. 6. Neutron Dose Rates From Water-Shielded Isotopic Power Sources of Curium-244 as a Function of Penetration Depth of Shielding Material. Center of source to dose point separation distance = 100 cm.

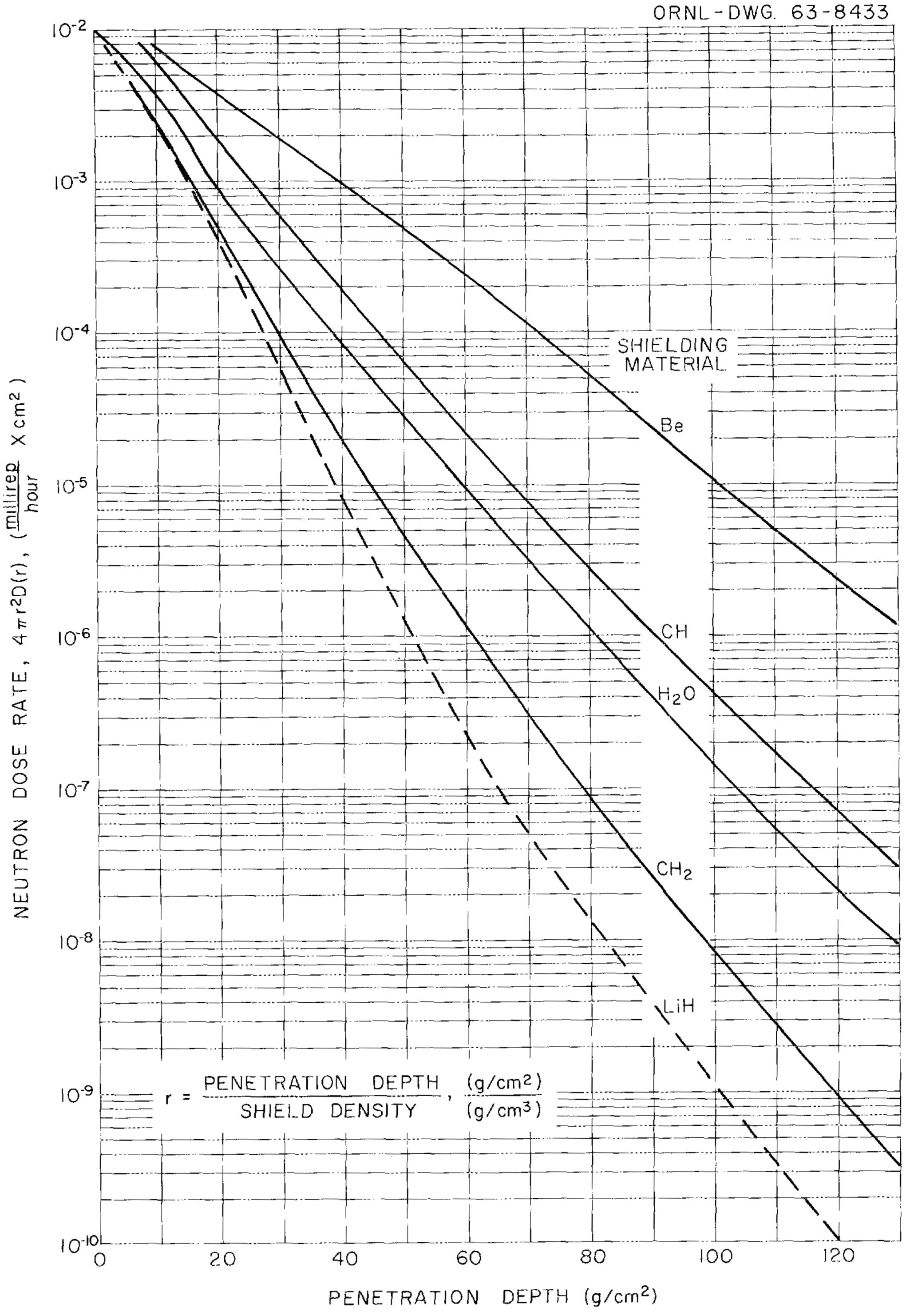

Fig. 7. Fast Neutron Dose Rate (Multiplied by $4\pi r^2$) in Various Materials as a Function of Penetration Depth From a Unit Point Isotropic Fission Source.

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REFERENCE COLUMN

B. CURIUM SESQUIOXIDE (Cm_2O_3)

1. Composition

a. Radionuclidic abundance

See Section I.A.1.

b. Radiochemical purity

Section Section I.A.1.

c. Phase composition of various curium oxides 25, 26, 27

$CmO_{2.00}$	$CmO_{1.77}$	$CmO_{1.68}$
$CmO_{1.91}$	$CmO_{1.72}$	$CmO_{1.50}$
$CmO_{1.85}$		

2. Specific Power

a. 2.53 watts/g of pure Cm_2O_3 (91.0% ^{244}Cm metal)
2.42 watts/g of Cm_2O_3 (86.9% Cm metal)

It is assumed that there are 81 curies/g of ^{244}Cm metal and 34.3 watts/kilocurie of ^{244}Cm.

b. 73.7 curies of ^{244}Cm per gram of pure Cm_2O_3 (91.0% ^{244}Cm metal) 2, 3, 4
70.5 curies of ^{244}Cm per gram of Cm_2O_3 (86.9% Cm metal)

3. Radiation

The radiation is given under Section I.A.3.

4. Critical Mass

See Section I.A.4.

5. Compatibility With Materials of Containment

A molybdenum alloy containing 0.5% titanium and 0.1% zirconium (TZM) was contacted with an oxide mixture containing 29 wt % $^{244}Cm_2O_3$, 57 wt % $^{241}AmO_2$, and 14 wt % $^{239}PuO_2$. Static capsule tests at 1100°C for periods of 250 and 1000 hr and at 2000°C for 25 hr showed no reaction with molybdenum, even though the oxide fuel was molten at 2000°C. 28

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REFERENCE COLUMN

System	Temp, °C	Time, hr	Atm	Extent of reaction	27
Cm_2O_3 powder in W crucible	1800	8	Vacuum	None detected visually	
Cm_2O_3 powder on W filament	2150 (melted)	1	4% H_2–96% He	No reaction, wetting, or penetration detected by metallography or by fission fragment autoradiography	
Cm_2O_3 powder on Ir filament	2150 (melted)	1	Helium	Curium penetration and surface reaction	
Cm_2O_3 powder on Pt–50% Rh filament	1700	10	O_2	No curium penetration, but possible surface reaction	

6. Thermophysical Properties

a. Density

11.67 ± 0.03 g/cm^3 – monoclinic — 29

11.94 ± 0.07 g/cm^3 – hexagonal — 25

b. Coefficient of thermal expansion

°C^{-1}	Temperature, °C	
8.90×10^{-6}	300	30 (Nd_2O_3)
10.60×10^{-6}	500	
11.35×10^{-6}	800	
11.41×10^{-6}	1050	

c. Specific heat and enthalpy

(1) Specific heat in cal g^{-1} °C^{-1}

$3.7 \times 10^{-2} + 2.91 \times 10^{-5}$ T (°K) — 31 (Am_2O_3)

(2) Enthalpy in calories

d. Temperatures of phase transformations

(1) Melting point – 1950°C — 32

– 2150°C — 27

(2) Boiling point – 3130°C — 31 (Am_2O_3)

(3) Cm_2O_3 (monoclinic) to Cm_2O_3 (orthorhombic) – 1900°C — 27

[redacted]

REFERENCE COLUMN

(4) Decomposition temperatures to lower oxides at oxygen pressures as cited: 27

Oxide	Temperature, °C $P_{O_2} = 10^{-5}$	3×10^{-3}	1 atm
$CmO_{2.00}$	360	391	440
$CmO_{1.91}$	Nonexistent	Nonexistent	520
$CmO_{1.85}$	520	625	>700
$CmO_{1.77}$	725	870	--
$CmO_{1.73}$	870	1065	--
$CmO_{1.68}$	1070	>1120	--
$CmO_{1.50}$	--	--	--

e. Latent heats of phase transformations

ΔH fusion 17 kcal/mole 31 (Am_2O_3)

ΔH vaporization 85 kcal/mole 31 (Am_2O_3)

f. Vapor pressure

Vaporization rate of Cm_2O_3 is as follows: 27

Temperature, °C	Rate, g cm^{-2} sec^{-1}
1914	4.0×10^{-6}
1929	9.0×10^{-6}
1958	15.9×10^{-6}
1986	17.0×10^{-6}
2023	59.8×10^{-6}
2041	76.5×10^{-6}
2109	119×10^{-6}
2122	221×10^{-6}

g. Thermal conductivity 33 (ThO_2)

cal cm^{-1} sec^{-1} $°C^{-1}$	Temperature, °C
0.0245	100
0.0204	200
0.0143	400
0.0104	600
0.0081	800
0.0073	1000
0.0060	1200
0.0059	1400

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REFERENCE COLUMN

h. Thermal diffusivity

cm^2/sec	Temperature, °C
0.0478	100
0.0111	800
0.00645	1400

Calculated by dividing the product of the specific heat and room temperature density into the thermal conductivity.

i. Viscosity

j. Surface tension

k. Total hemispherical emittance

l. Spectral emissivity

0.20 to 0.57 — 19 (ThO_2)

The precise value is a function of the roughness of the material surface, the presence of impurities, and the effects of radiation.

m. Crystallography — 29

Cm_2O_3: Monoclinic, beta-type rare-earth oxide

a = 14.28
b = 3.65
c = 8.92
β = 100°24'

Space group

C_{2h}^3

Six units per cell

Cm_2O_3: Orthorhombic

a = 7.993
b = 6.188
c = 3.368

n. Solubilities

Insoluble in water — 20

o. Diffusion rates

[redacted]

[redacted]

REFERENCE COLUMN

7. Mechanical Properties

a. Hardness

b. Crush strength
$1900\ kg/cm^2$ 34 (CeO_2)

8. Chemical Properties

a. Heat and free energy of formation, entropy

(1) Heat of formation
$\Delta H^\circ_f = -440$ kcal/mole 31
(estimated from Am_2O_3 and Pu_2O_3)

(2) Free energy of formation
$\Delta F^\circ_f = -420$ kcal/mole 31
(estimated from Am_2O_3 and Pu_2O_3)

(3) Entropy (estimated) 35
Cm_2O_3: $S^\circ_{298} = 38.4$ eu
CmO_2: $S^\circ_{298} = 20.9$ eu

b. Chemical reactions and reaction rates (oxygen, nitrogen, water, steam, hydrogen liquid metals, other)

(1) Oxygen at room temperature — slow

(2) Oxygen at elevated temperature — fast 20

(3) Nitrogen — no reaction

(4) Water — possible hydration reaction

(5) Inorganic acids — soluble in acids

9. Biological Tolerances

Maximum permissible body burdens and maximum permissible concentrations of ^{244}Cm in air and in water are given under Section I.A.9. 24

10. Shielding Data

The dose rates are given under Section I.A.10.

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REFERENCE COLUMN

C. CURIUM OXYSULFIDE (Cm_2O_2S)

1. Composition

a. Radionuclidic abundance

See Section I.A.1.

b. Radiochemical purity

See Section I.A.1.

2. Specific Power

a. 2.46 watts/g of pure Cm_2O_2S (88.4% ^{244}Cm metal)
2.35 watts/g of Cm_2O_2S (84.4% ^{244}Cm metal)

It is assumed that there are 81 curies/g of ^{244}Cm and 34.3 watts/kilocurie of ^{244}Cm.

b. 71.6 curies of ^{244}Cm per gram of pure Cm_2O_2S (88.4% ^{244}Cm metal) — 2, 3, 4
68.4 curies of ^{244}Cm per gram of Cm_2O_2S (84.4% ^{244}Cm metal)

3. Radiation

The radiation is given under Section I.A.3.

4. Critical Mass

See Section I.A.4.

5. Compatibility With Materials of Containment

6. Thermophysical Properties

a. Density

9.95 g/cm^3 — 36 (Pu_2O_2S)

b. Coefficient of thermal expansion

$°C^{-1}$	Temperature, °C	Reference
8.90×10^{-6}	300	30 (Nd_2O_3)
10.60×10^{-6}	500	
11.35×10^{-6}	800	
11.41×10^{-6}	1050	

[redacted]

REFERENCE COLUMN

c. Specific heat and enthalpy

(1) Specific heat in cal g^{-1} $°C^{-1}$

$3.62 \times 10^{-2} + 2.83 \times 10^{-5}$ T (°K) — 31 (Am_2O_3)

(2) Enthalpy in calories

d. Temperatures of phase transformations

(1) Melting point – 2000°C — 37 (Ce_2O_2S)

(2) Boiling point – 3130°C — 31 (Am_2O_3)

e. Latent heats of phase transformations

ΔH fusion 17 kcal/mole — 31 (Am_2O_3)

ΔH vaporization 85 kcal/mole — 31 (Am_2O_3)

f. Vapor pressure

g. Thermal conductivity

cal cm^{-1} sec^{-1} $°C^{-1}$	Temperature, °C	
0.0245	100	33 (ThO_2)
0.0081	800	
0.0059	1400	

h. Thermal diffusivity

cm^2/sec	Temperature, °C
0.0528	100
0.0116	800
0.00708	1400

Calculated by dividing the product of the specific heat and room temperature density into the thermal conductivity.

i. Viscosity

j. Surface tension

k. Total hemispherical emittance

l. Spectral emissivity

0.20 to 0.57 — 19 (ThO_2)

The emissivity value depends on the roughness of the material surface, radiation effects, and the presence of impurities.

[redacted]

REFERENCE COLUMN

m. Crystallography

hexagonal | 36 (Pu_2O_2S)

a = 4.008 A

c = 6.769 A

The cell constants should be slightly smaller for Cm_2O_2S due to the actinide contraction.

n. Solubilities

(1) Soluble in strong acids (Ce_2O_2S) | 38

(2) Insoluble in acetic acid (Ce_2O_2S) | 38

o. Diffusion rates

7. Mechanical Properties

a. Hardness

b. Crush strength

8. Chemical Properties

a. Heat and free energy of formation, entropy

(1) Heat of formation

ΔH°_f = -430 kcal/mole | 37

(approximated by Ce_2O_2S)

(2) Free energy of formation

ΔF°_f = -414 kcal/mole

(calculated by $\Delta F^\circ_f = \Delta H^\circ_f - T\Delta S^\circ_f$)

(3) Entropy

S°_{298} = 34.3 eu | 39

(calculated by W. Latimer's method)

b. Chemical reactions and reaction rates (oxygen, nitrogen, water, steam, hydrogen, liquid metals, other) | 38

(1) Air at room temperature — slow

(2) Air at elevated temperature — fast

(3) Water at room temperature — no reaction

(4) Inorganic acids at room temperature — reacts

[redacted]

REFERENCE COLUMN

9. Biological Tolerances

Maximum permissible body burdens and maximum permissible concentrations of ^{244}Cm in air and in water are given under the ^{244}Cm Metal Source Form, Section I.A.9. 24

10. Shielding Data

The dose rates are given under the ^{244}Cm Metal Source Form, Section I.A.10.

REFERENCE COLUMN

D. CURIUM FLUORIDE (CmF_3)

1. Composition

a. Radionuclidic abundance

See Section I.A.1.

b. Radiochemical purity

See Section I.A.1.

2. Specific Power

a. 2.25 watts/g of pure CmF_3 (81.1% ^{244}Cm metal)
2.15 watts/g of CmF_3 (77.5% ^{244}Cm metal)

It is assumed that there are 81 curies/g of ^{244}Cm and 34.3 watts/kilocurie of ^{244}Cm.

b. 65.7 curies of ^{244}Cm per gram of pure CmF_3 (81.1% ^{244}Cm metal) — 2, 3, 4
62.7 curies of ^{244}Cm per gram of CmF_3 (77.5% ^{244}Cm metal)

3. Radiation

The radiation is given under Section I.A.3.

4. Critical Mass

See Section I.A.4.

5. Compatibility With Materials of Containment

6. Thermophysical Properties

a. Density

9.80 g/cm^3 — 40

b. Coefficient of thermal expansion

$a = 19.74 \times 10^{-6} + 2.62 \times 10^{-8}\ t + 0.15 \times 10^{-10}\ t^2$ — 41 (BaF_2)

(t is in °C with a temperature range of 26-296°C)

c. Specific heat and enthalpy

(1) Specific heat in cal g^{-1} °C^{-1}

$7.21 \times 10^{-2} + 2.06 \times 10^{-5}\ T$ (°K) — 31 (AmF_3)

[redacted]

REFERENCE COLUMN

(2) Enthalpy in calories

$H_T - H_{298} = 21\ T + 3.5 \times 10^{-3}\ T^2$ — 31

(estimated from other actinide data)

d. Temperatures of phase transformations

(1) Melting point — 1406°C — 42

(2) Boiling point — 2330°C — 12

This value is the average of the boiling points of LaF_3, CeF_3, and PrF_3.

e. Latent heats of phase transformations

ΔH fusion 9 kcal/mole — 31 (CeF_3)

ΔH vaporization 62 kcal/mole — 31 (CeF_3)

f. Vapor pressure

Vapor pressure, torr	Temperature, °C	Reference
5.07×10^{-7}	853	43
7.18×10^{-6}	943	
1.486×10^{-4}	1033	
1.725×10^{-3}	1141	
5.820×10^{-3}	1196	

Vapor pressures are for AmF_3.

g. Thermal conductivity

$cal\ cm^{-1}\ sec^{-1}\ °C^{-1}$	Temperature, °C	Reference
0.0296	0	44 (BaF_2)
0.0251	100	

h. Thermal diffusivity

cm^2/sec	Temperature, °C
0.0399	0
0.0321	100

Calculated by dividing the product of the specific heat and the room temperature density into the thermal conductivity.

i. Viscosity

j. Surface tension

[redacted]

REFERENCE COLUMN

k. Total hemispherical emittance

A value of 0.9 can be assumed.

l. Spectral emissivity

m. Crystallography

hexagonal, LaF_3-type, space group $P6_3/mmc$ 45

a = 4.041 ± 0.001 A   c = 7.179 ± 0.002 A

n. Solubilities

o. Diffusion rates

7. Mechanical Properties

a. Hardness

b. Crush strength

8. Chemical Properties

a. Heat and free energy of formation, entropy

(1) Heat of formation

ΔH°_f = -395 kcal/mole 31

(estimated from other actinide data)

(2) Free energy of formation

ΔF°_f = -375 kcal/mole 31

(estimated from other actinide data)

(3) Entropy

S°_{298} = 29 eu 31

(estimated from other actinide data)

b. Chemical reactions and reaction rates (oxygen, nitrogen, water, steam, hydrogen, liquid metals, other)

(1) Air at room temperature — no reaction

(2) Air at elevated temperature — forms oxyfluoride 20

(3) Nitrogen — no reaction

(4) Water — insoluble

(5) Inorganic acids — insoluble in weak inorganic acid

REFERENCE COLUMN

9. Biological Tolerances

Maximum permissible body burdens and maximum permissible concentrations of ^{244}Cm in air and in water are given under Section I.A.9. 24

10. Shielding Data

The dose rates are given under Section I.A.10.

II. CURIUM-242 — REFERENCE COLUMN

A. CURIUM-242 OXIDE CERMET — HALF-LIFE: 163 d — 1, 2, 5, 7

1. Composition

a. Radionuclidic abundance

The composition of the product will depend on the irradiation history of the ^{241}Am target as well as the cooling time after removal from the pile. The product is expected to be at least 40% ^{242}Cm. If it is not this high, an Am-Cm separation is used to lower the americium content of the product.

The analysis for a typical batch of ^{241}Am with a total integrated neutron dose of 1.3×10^{21} and with a 90-day cooling and processing period (with all the plutonium removed) is as follows: 46

Isotope	% Abundance
^{241}Am	47.5
^{242}Am	1.6
^{243}Am	7.7
^{242}Cm	41.9
^{243}Cm	0.5
^{244}Cm	0.8

The decay of ^{242}Cm to ^{238}Pu is illustrated in the following table. A 10-g product with 40% ^{242}Cm and 60% other actinides is assumed. The decay is shown for 163 days.

Time, days	^{242}Cm, g	^{238}Pu, g
0	4.00	0
16	3.73	0.27
32	3.48	0.52
65	3.03	0.97
81.5	2.83	1.17
98	2.46	1.54
163	2.00	2.00

The oxide mixture will be AmO_2 and Cm_2O_3. This will be suspended in a neutral matrix material to give the prescribed power density:

30 vol % oxide mixture
70 vol % matrix material

[redacted]

REFERENCE COLUMN

b. Radiochemical purity

The only important heat contributor to the ^{242}Cm-source material is ^{242}Cm. The following table shows the contribution of each isotope to 10 g of the oxide mixture. 46

Heat Contribution of Each Isotope of the ^{242}Cm Product

Nuclide	Half-life	Specific activity, w/g	% of nuclide	Heat contribution watts	Heat contribution %
^{241}Am	458 y	0.106	47.5	0.50	0.1
^{242}Am	152 y	0.034	1.6	0.05	0.01
^{243}Am	7650 y	0.006	7.7	0.005	0.001
^{242}Cm	163 d	120.0	41.9	502.8	99.8
^{243}Cm	32 y	1.44	0.5	0.07	0.015
^{244}Cm	18.1 y	2.78	0.8	0.22	0.05
^{238}Pu	89 y	0.55			

The ^{242}Cm product has contained up to 30 curies of ^{144}Ce per 8.33 g of ^{242}Cm. Trace amounts of ^{103}Ru-^{106}Ru and ^{95}Zr-^{95}Nb have been found in the feed but do not contribute materially to the power or radiation of the source.

The above contaminations can be reduced to much lower levels by additional processing.

2. Specific Power

a. 42.8 watts/g of AmO_2-Cm_2O_3 (35.7% ^{242}Cm metal)

It is assumed that there are 3320 curies/g of ^{242}Cm and 36.1 watts/kilocurie of ^{242}Cm. 6

b. 1186 curies of ^{242}Cm per gram of AmO_2-Cm_2O_3 (35.7% ^{242}Cm metal) 5

3. Radiation

a. Alpha particles 5

Nuclide	Max E, Mev	Avg E, Mev	Abundance, %	w/kilocurie	Particles w^{-1} sec^{-1}
^{242}Cm	6.11	6.11	73.7	36.10	0.755×10^{12}
	6.066	6.066	26.3		0.270×10^{12}
Total power				36.10	

[redacted]

[redacted]

REFERENCE COLUMN

The amount of helium produced by alpha decay of ^{242}Cm as a function of time is given in the following table.

Volume of Helium as a Function of Decay Time

cm^3 of He per g of ^{242}Cm (standard conditions)	Time	
	Days	Half-lives
11.9	32.6	0.2
22.4	65.2	0.4
31.5	97.8	0.6
39.4	130.4	0.8
46.3	163	1.0
59.8	244	1.5
69.4	326	2.0
80.9	489	3.0
86.7	652	4.0
89.6	815	5.0
92.4	1630	10.0

b. Beta particles – none

c. Gamma

In addition to the gammas from the alpha decay, 5
there are the prompt and fission-product gammas from the spontaneous fission of ^{242}Cm ($T_{1/2}$ = 7.2×10^6 y). The gamma-emission rates are given in the following table.

Gamma-emission rate,* photons sec^{-1} g^{-1}	Photon energy, Mev
^{242}Cm gammas	
0.27×10^{14}	0.044
1.42×10^{10}	0.10
2.83×10^9	0.158
Prompt gammas	
2.44×10^7	1.0
6.09×10^6	1.5
6.45×10^6	2.3
1.15×10^6	3.0
1.52×10^6	5.0

[redacted]

[redacted]

REFERENCE COLUMN

Gamma-emission rate,* photons sec^{-1} g^{-1}	Photon energy, Mev
Fission-product gammas	
2.16×10^7	0.63
7.99×10^6	1.1
9.36×10^6	1.55
1.80×10^6	2.38
2.66×10^6	2.75

*120-watt source.

d. Bremsstrahlung — none

e. Neutrons

2.30×10^7 neutrons sec^{-1} g^{-1} of ^{242}Cm from spontaneous fission (120-watt source) 5

2.0×10^7 neutrons sec^{-1} g^{-1} of ^{242}Cm from (α,n) reaction on oxygen in Cm_2O_3 (120-watt source)

The energy distribution of spontaneous fission neutrons from ^{242}Cm is given in the following table. 3

Spontaneous Fission Neutrons From ^{242}Cm

Energy, Mev	Abundance,* neutrons sec^{-1} g^{-1} of ^{242}Cm
0.3-0.4	7.7×10^5
0.4-0.6	1.6×10^6
0.6-0.8	1.6×10^6
0.8-1.0	1.4×10^6
1.0-1.2	1.4×10^6
1.2-1.4	1.4×10^6
1.4-1.6	1.2×10^6
1.6-1.8	1.1×10^6
1.8-2.0	1.0×10^6
2.0-2.2	9.1×10^5
2.2-2.4	8.4×10^5
2.4-2.6	8.0×10^5
2.6-2.8	6.5×10^5
2.8-3.0	5.5×10^5
3.0-3.2	5.0×10^5
3.2-3.4	5.0×10^5
3.4-3.6	4.7×10^5
3.6-3.8	3.7×10^5
3.8-4.0	4.1×10^5

[redacted]

[redacted]

REFERENCE COLUMN

Spontaneous (continued)

Energy, Mev	Abundance,* neutrons sec^{-1} g^{-1} of ^{242}Cm
4.0-4.4	5.2×10^5
4.4-4.8	4.4×10^5
4.8-5.2	3.2×10^5
5.2-5.6	2.5×10^5
5.6-6.0	1.9×10^5
6.0-6.4	1.5×10^5
6.4-6.8	1.1×10^5
6.8-7.2	7.5×10^4
7.2-7.6	5.6×10^4
7.6-8.0	4.7×10^4
8.0-8.8	5.0×10^4
8.8-9.6	1.5×10^4
9.6-10.4	1.6×10^4
10.4-11.2	1.0×10^4
11.2-12.8	7.1×10^3

*120-watt source.

The energy distribution of neutrons occurring 3
as a result of a collision of fast alpha particles from ^{242}Cm decay with oxygen atoms in Cm_2O_3 is given in the following table.

Neutrons From (α,n) Reactions With Oxygen

Energy, Mev	Abundance,* neutrons sec^{-1} g^{-1} of ^{242}Cm
0.2	5.0×10^3
0.4	1.0×10^4
0.6	2.0×10^4
0.8	2.5×10^4
1.0	7.6×10^4
1.2	1.5×10^5
1.4	2.8×10^5
1.6	4.5×10^5
1.8	7.6×10^5
2.0	1.0×10^6
2.2	1.3×10^6
2.4	1.7×10^6
2.6	2.0×10^6
2.8	2.1×10^6

[redacted]

REFERENCE COLUMN

Neutrons (continued)

Energy, Mev	Abundance,* neutrons sec^{-1} g^{-1} of ^{242}Cm
3.0	2.1×10^6
3.2	2.1×10^6
3.4	1.8×10^6
3.6	1.5×10^6
3.8	1.0×10^6
4.0	6.5×10^5
4.2	4.0×10^5
4.4	2.8×10^5
4.6	1.8×10^5
4.8	5.0×10^4

*120-watt source.

4. Critical Mass

5. Compatibility With Materials of Containment

Tests at 1100°C for 1000 hr and at 2000°C for 25 hr with an oxide mixture containing 29 wt % Cm_2O_3, 57 wt % AmO_2, and 14 wt % PuO_2 showed that this oxide mixture was compatible with the alloy Mo-0.5% Ti-0.1% Zr (TZM). 28

With the use of iridium in a metal-metal oxide cermet, alloying of iridium with molybdenum was observed at 2000°C. Also the molten oxide mix appeared to react with iridium to form a lower melting alloy. At 1000°C the reaction between iridium and molybdenum was too slow to be observed, at least over a period of time of 1000 hr.

6. Thermophysical Properties

a. Density

The density of oxide mixture is equal to 11.67 g/cm^3. 29

b. Coefficient of thermal expansion

30 (Nd_2O_3)

Linear coefficient of expansion, $°C^{-1}$	Temperature, °C
8.90×10^{-6}	300
10.60×10^{-6}	500
11.35×10^{-6}	800
11.41×10^{-6}	1050

The thermal coefficient of expansion of the cermet will depend markedly on the matrix material.

REFERENCE COLUMN

c. Specific heat and enthalpy

(1) Specific heat

Values will depend on the matrix material.

(2) Enthalpy

Values will depend on the matrix material.

d. Temperatures of phase transformations

(1) Melting point – 2000-2200°C for AmO_2-Cm_2O_3 mixture — 32

(2) Boiling point – 3400°C for AmO_2-Cm_2O_3 mixture — 31 (Am_2O_3)

e. Latent heats of phase transformations

ΔH fusion 17 kcal/mole — 31 (Am_2O_3)

ΔH vaporization 85 kcal/mole — 31 (Am_2O_3)

f. Vapor pressure

Will depend primarily on the matrix metal and on the temperature.

g. Thermal conductivity — 33 (ThO_2)

cal cm^{-1} sec^{-1} $°C^{-1}$	Temperature, °C
0.0245	100
0.0143	400
0.0081	800
0.0059	1400

With the selection of the proper matrix material for cermet, it should be possible to reach a 0.06 cal cm^{-1} sec^{-1} $°C^{-1}$ thermal conductivity for the cermet.

h. Thermal diffusivity

Values will depend on the matrix material.

i. Viscosity

The viscosity will depend primarily on the properties of the matrix metal.

j. Surface tension

The surface tension will depend primarily on the properties of the matrix metal.

[redacted]

REFERENCE COLUMN

k. Total hemispherical emittance

l. Spectral emissivity

0.20-0.57 — 19 (ThO_2)

The matrix material will have a pronounced effect on the emissivity.

m. Crystallography — 29

Cm_2O_3: Monoclinic, beta-type rare-earth oxide

a = 14.28
b = 3.65
c = 8.92
β = 100°24'

Space group

C^3_{2h}

Six units per cell

Cm_2O_3: Orthorhombic

a = 7.993
b = 6.188
c = 3.368

n. Solubilities

Insoluble in water — 20 (Cm_2O_3)

o. Diffusion rates

7. Mechanical Properties

The mechanical properties of the metal-oxide mixture will depend strongly on the properties of the matrix metal.

a. Hardness

b. Crush strength

8. Chemical Properties

a. Heat and free energy of formation, entropy

The thermodynamic properties of a metal-oxide mixture will depend strongly on the metal matrix.

(1) Heat of formation

ΔH°_f = -440 kcal/mole — 31

(estimated from Am_2O_3 and Pu_2O_3)

[redacted]

[redacted]

REFERENCE COLUMN

(2) Free energy of formation

ΔF°_f = -420 kcal/mole 31

(estimated from Am_2O_3 and Pu_2O_3)

(3) Entropy (estimated) 35

Cm_2O_3: $S^\circ_{298} = 38.4$ eu

CmO_2: $S^\circ_{298} = 20.9$ eu

b. Chemical reactions and reaction rates (oxygen, nitrogen, water, steam, hydrogen liquid metals, other)

These properties will depend on the matrix material.

9. Biological Tolerances

The ^{242}Cm tolerances taken from Ref 24 are given in the table on the following page. 24

10. Shielding Data

Gamma dose rates with water, iron, lead, and uranium shielding are given in Figs. 8-12 for ^{242}Cm power sources of 100, 200, 500, 1000, 2000, 5000, 10,000, and 20,000 watts. Neutron dose rates with water shielding are given in Fig. 13. Neutron dose rates on shielding with Be, CH, CH_2, or LiH can be estimated by using Fig. 13 in conjunction with Fig. 14. 5

[redacted]

Maximum Permissible Body Burdens and Maximum Permissible Concentrations for Radionuclides in Air and in Water for Occupational Exposure[24]

Radionuclide and type of decay	Organ of reference (critical organ underscored)	Max. permissible burden in total body, q(μc)	Maximum permissible concentrations, μc/cm³ For 40-hr week Water	For 40-hr week Air	For 168-hr week Water	For 168-hr week Air
(Sol)	GI (LLI)*		7×10^{-4}	2×10^{-7}	2×10^{-4}	5×10^{-8}
	Liver	0.05	3×10^{-3}	10^{-10}	9×10^{-4}	4×10^{-11}
	Bone	0.09	5×10^{-3}	2×10^{-10}	2×10^{-3}	8×10^{-11}
	Kidney	0.2	9×10^{-3}	4×10^{-10}	3×10^{-3}	10^{-10}
	Total Body	0.2	0.01	6×10^{-10}	5×10^{-3}	2×10^{-10}
(Insol)	Lung			2×10^{-10}		6×10^{-11}
	GI (LLI)*		7×10^{-4}	10^{-7}	3×10^{-4}	4×10^{-8}

*The abbreviations GI and LLI refer to the gastrointestinal tract and lower large intestine, respectively.

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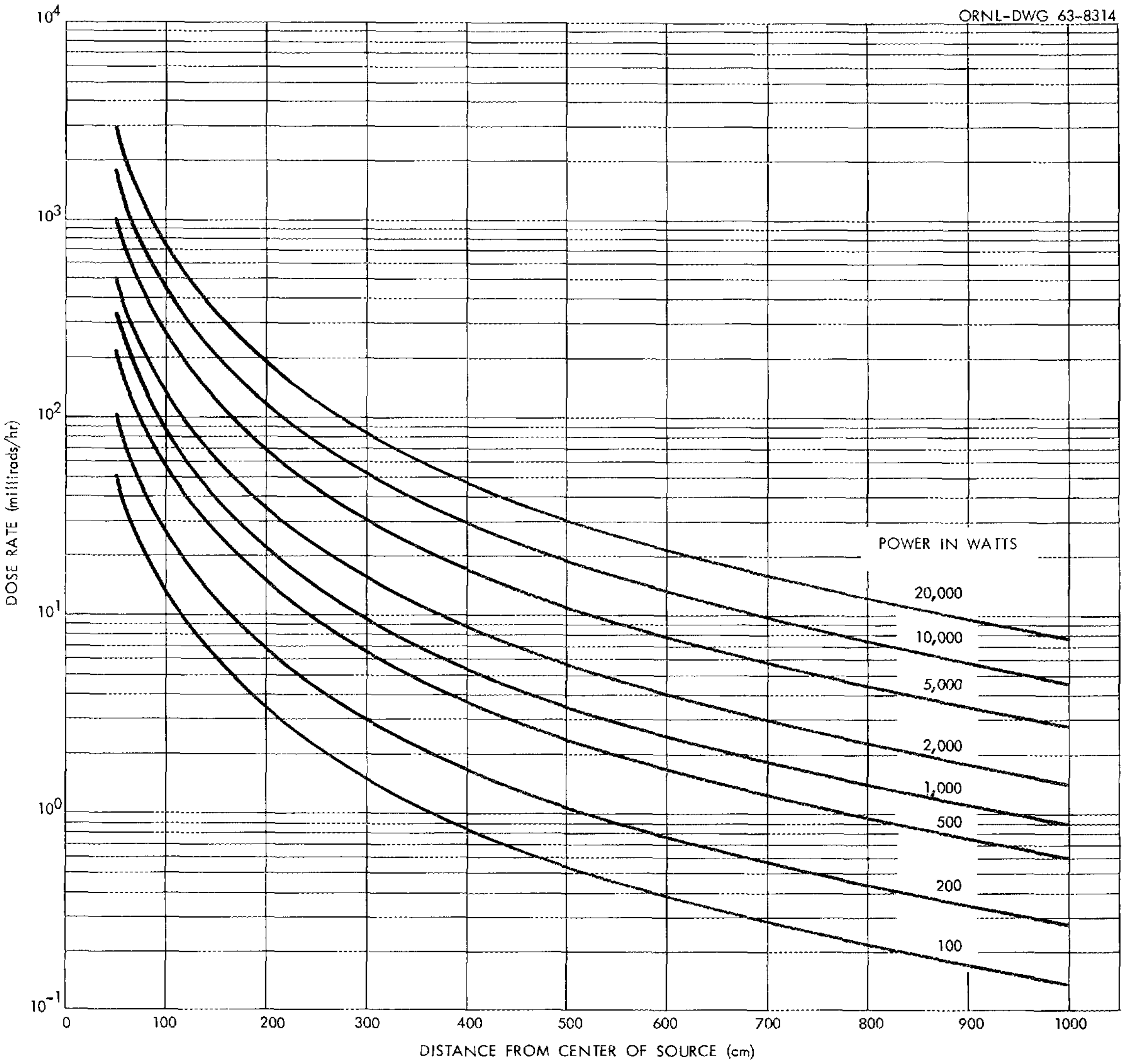

Fig. 8. Gamma Dose Rates From Unshielded Isotopic Power Sources of Curium-242 as a Function of Distance From Center of Source.

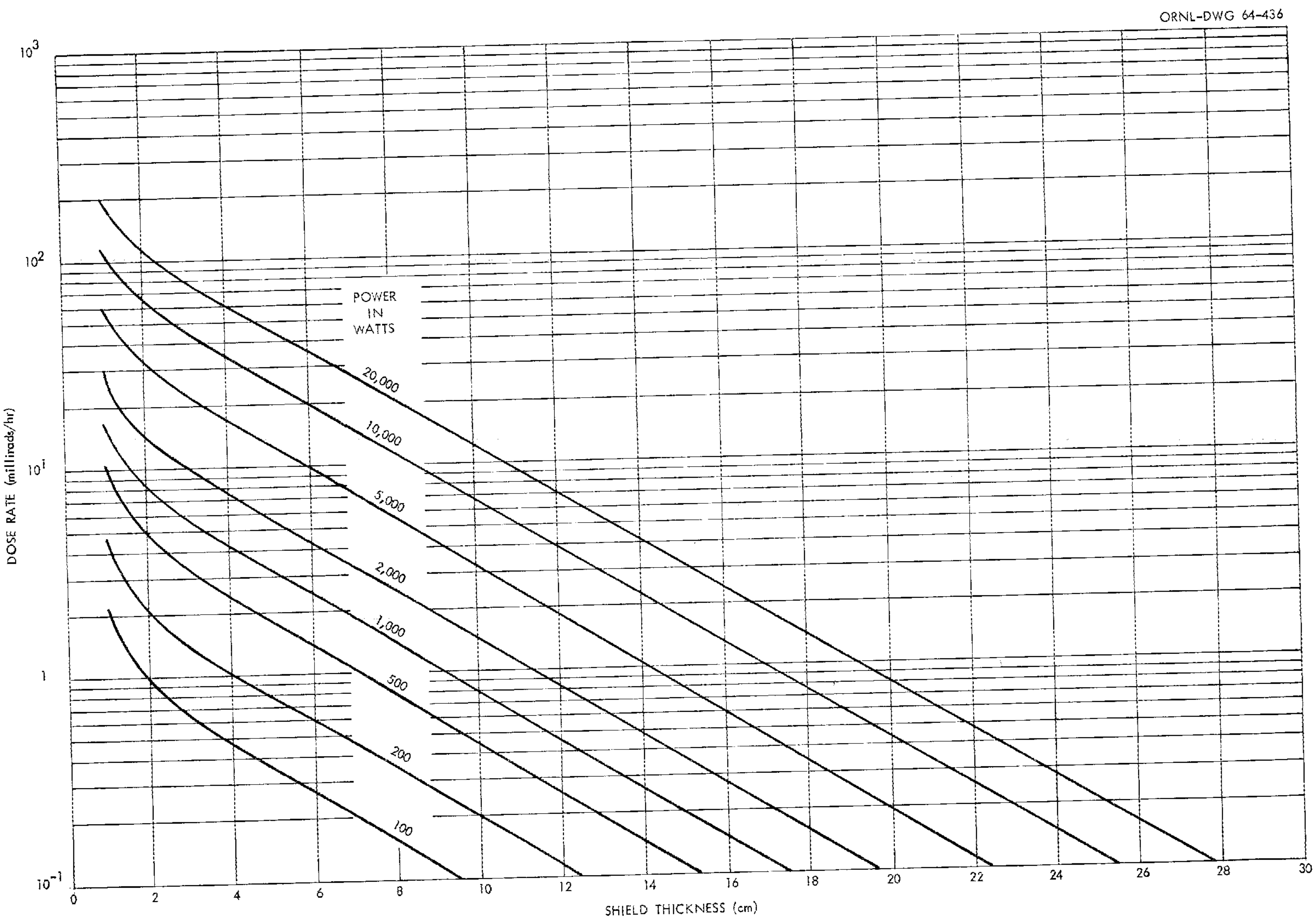

Fig. 9. Gamma Dose Rates From Iron-Shielded Isotopic Power Sources of Curium-242. Center of source to dose point separation distance = 100 cm.

UNCLASSIFIED

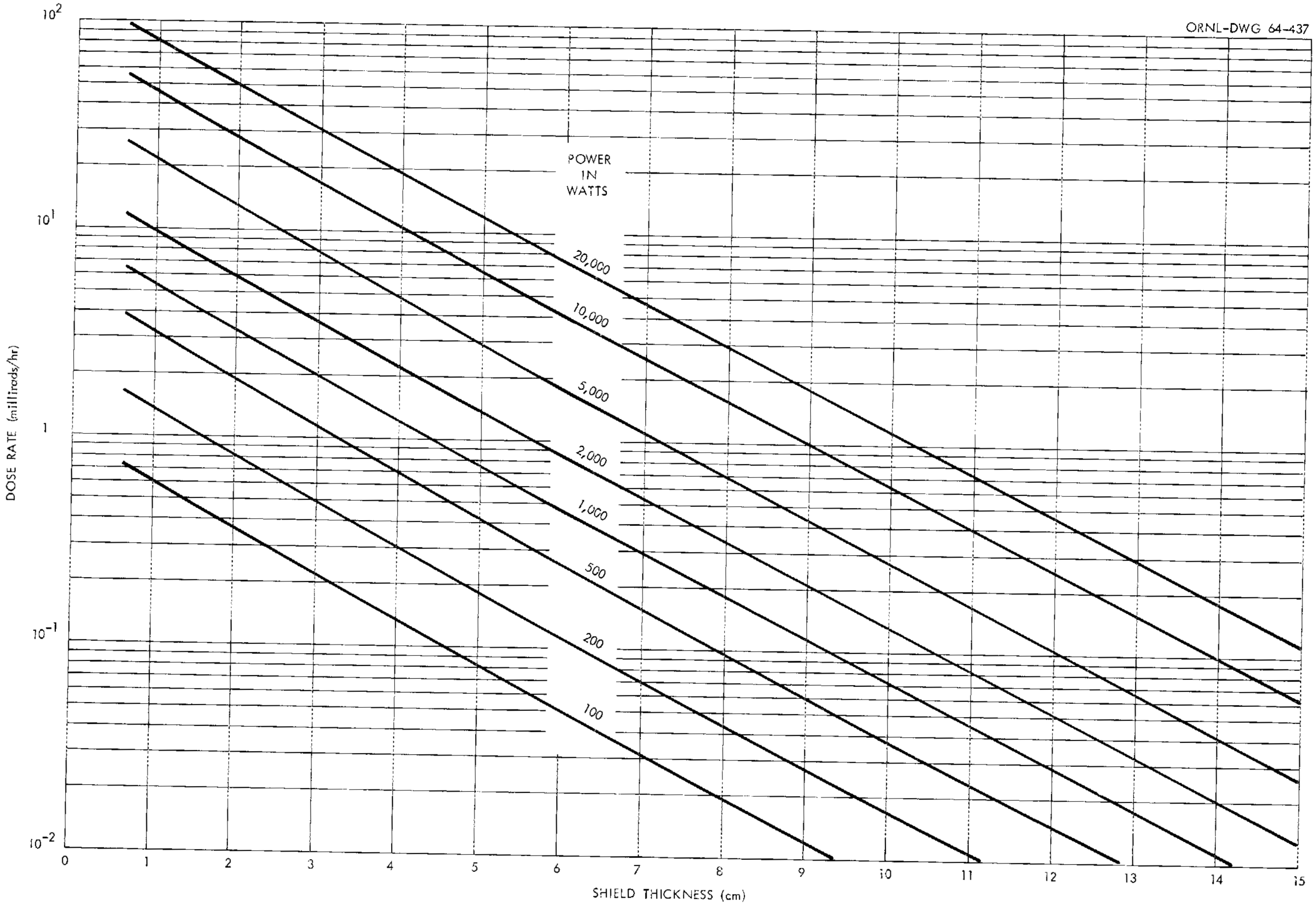

Fig. 10. Gamma Dose Rates From Lead-Shielded Isotopic Power Sources of Curium-242. Center of source to dose point separation distance = 100 cm.

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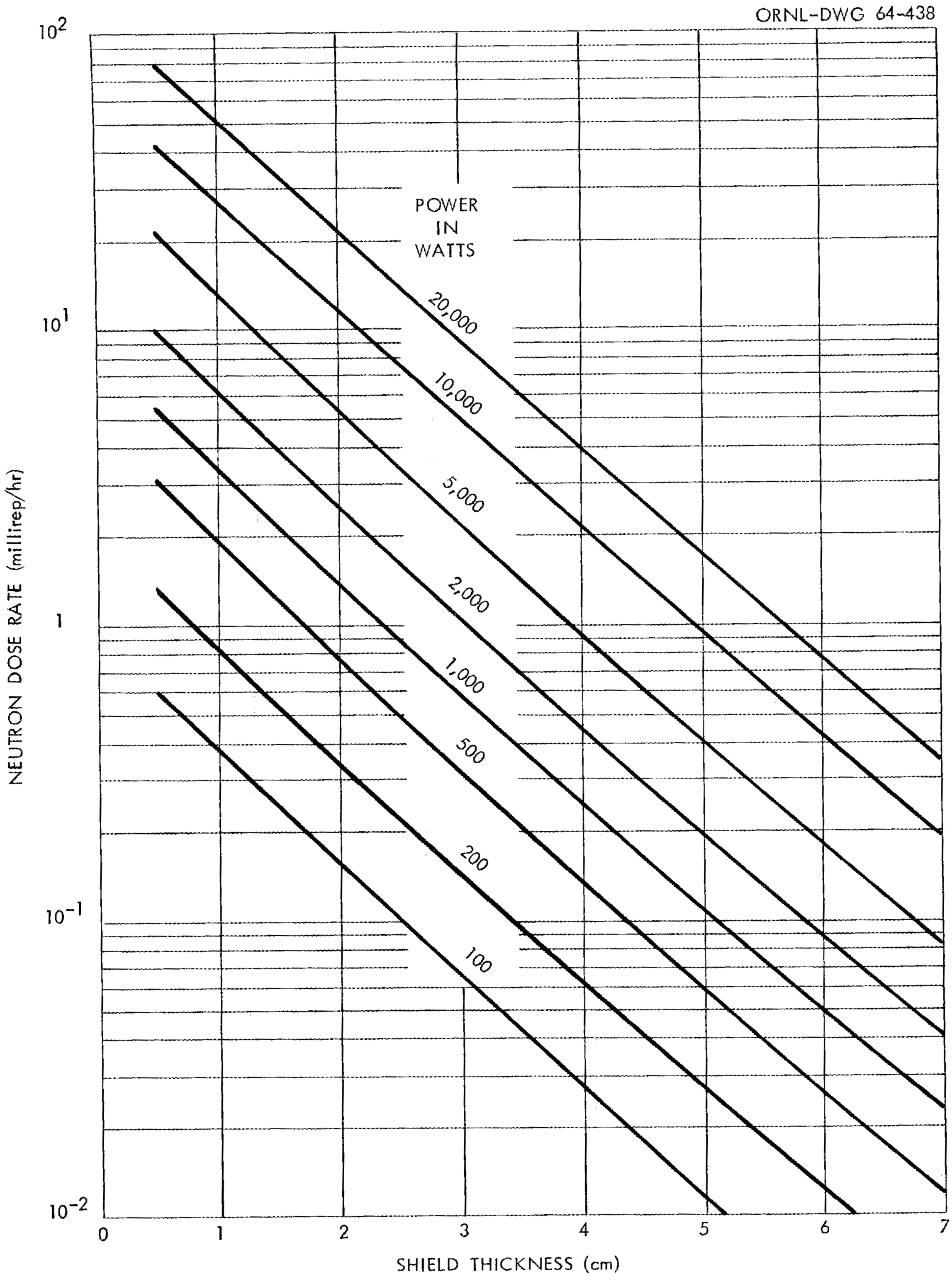

Fig. 11. Gamma Dose Rates From Uranium-Shielded Isotopic Power Sources of Curium-242. Center of source to dose point separation distance = 100 cm.

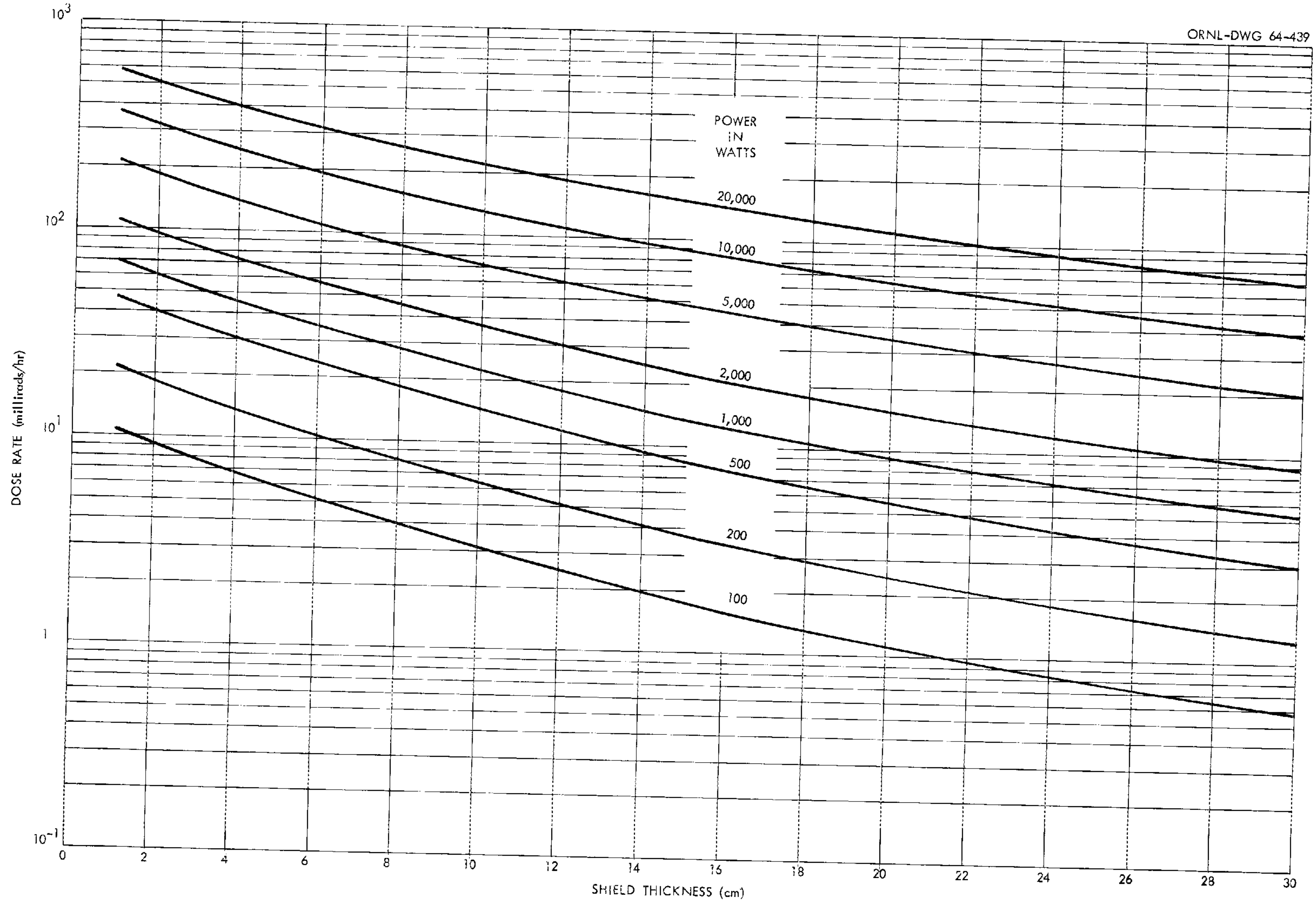

Fig. 12. Gamma Dose Rates From Water-Shielded Isotopic Power Sources of Curium-242. Center of source to dose point separation distance = 100 cm.

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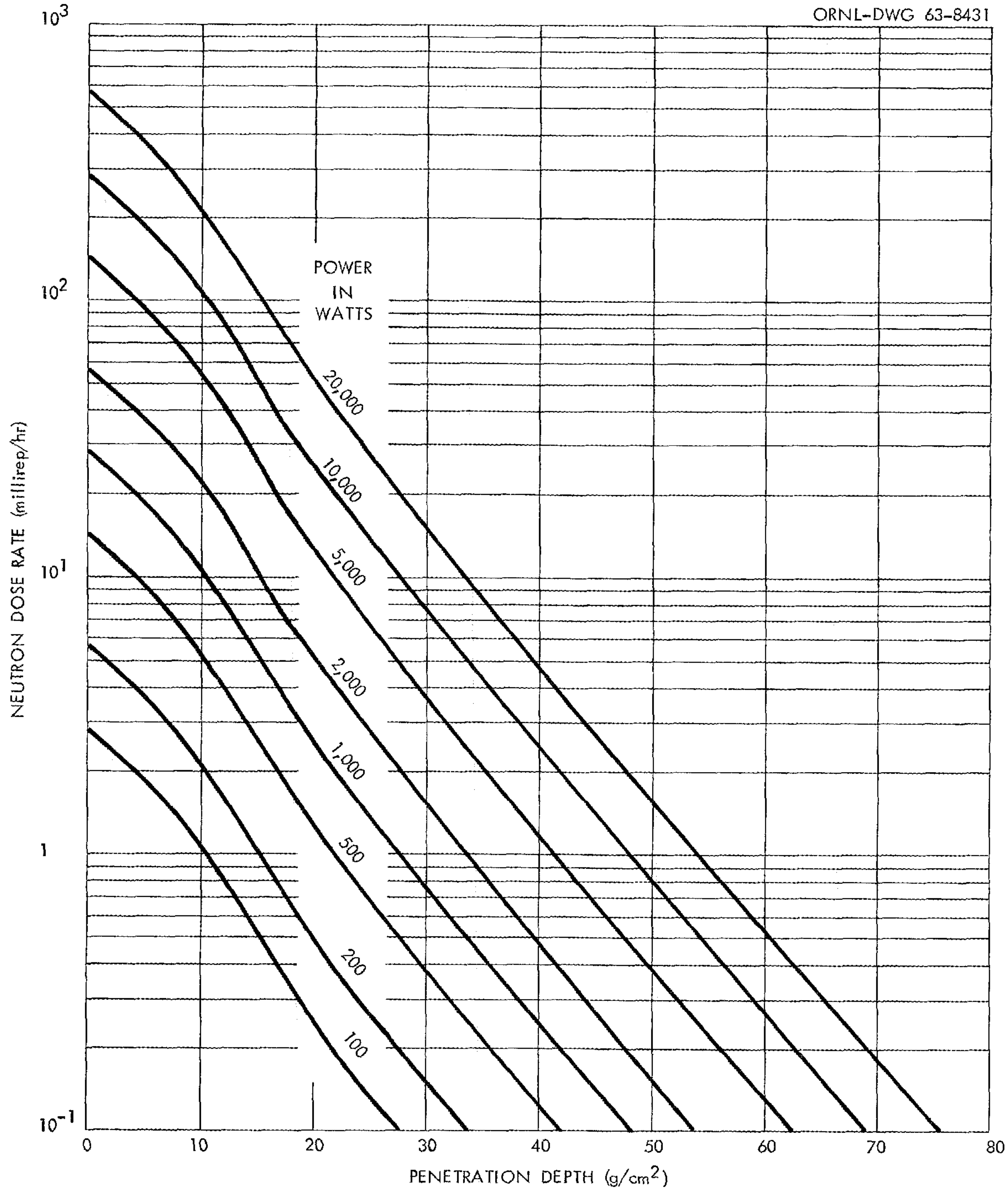

Fig. 13. Neutron Dose Rates From Water-Shielded Isotopic Power Sources of Curium-242 as a Function of Penetration Depth of Shielding Material. Center of source to dose point separation distance = 100 cm. Refer to Fig. 9 to obtain dose rates through other materials.

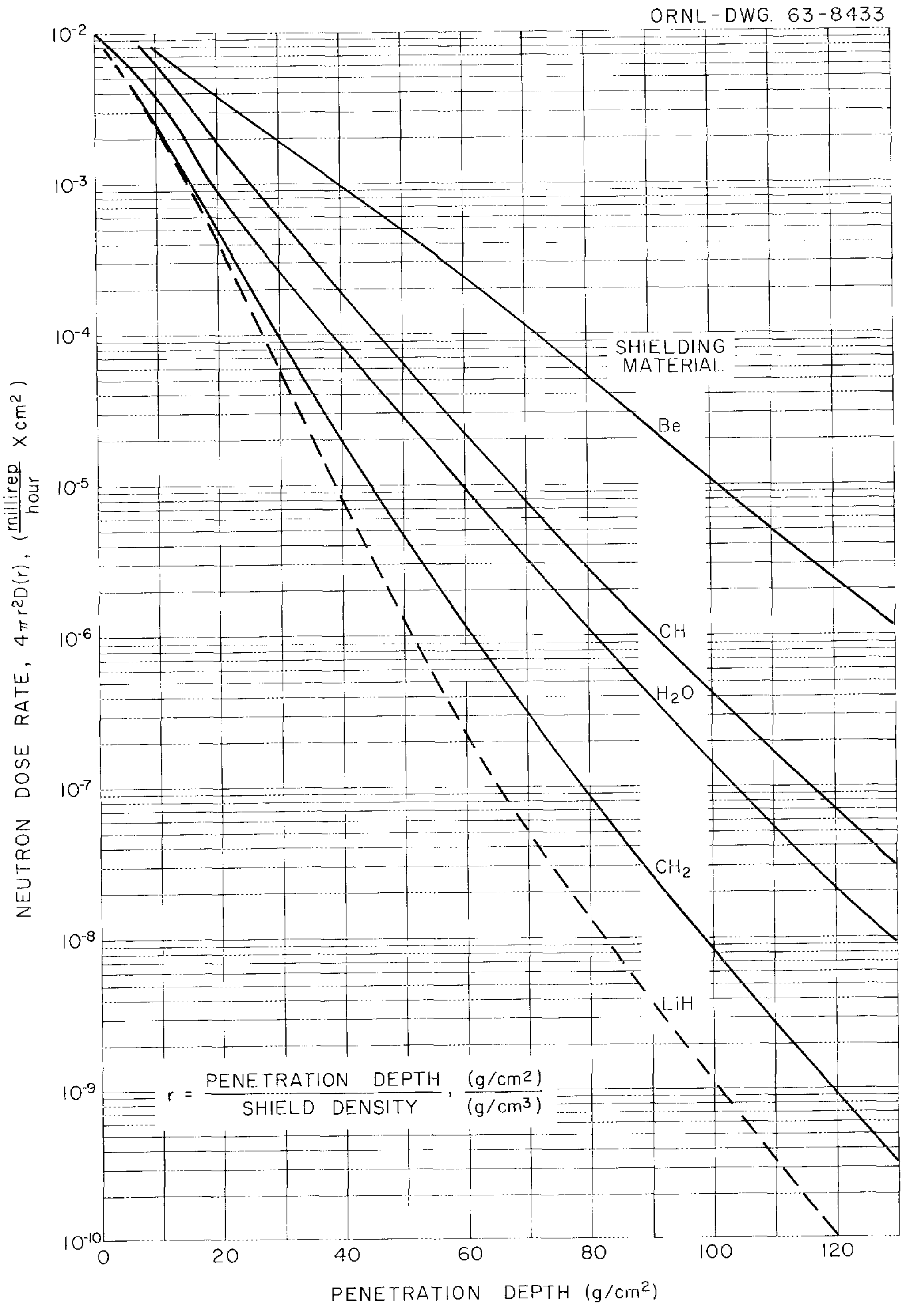

Fig. 14. Fast Neutron Dose Rate (Multiplied by $4\pi r^2$) in Various Materials as a Function of Penetration Depth From a Unit Point Isotropic Fission Source.

III. REFERENCES FOR CURIUM

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